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Directional Hub Slotted Aloha Medium Access Control Protocol for Wireless Sensor Networks with Directional Antennas

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***Abstract* — The primary contribution of this paper lies in evaluating the throughput performance of a wireless sensor network (WSN) with realistic directional antennas. A simple medium access control (MAC) protocol is proposed, based on the Slotted Aloha protocol but designed to support multiple directional antennas at the hub. A brief review of the throughput analysis for the traditional Aloha protocols is given, followed by an analytical model for the throughput performance for directional hub Aloha protocols. Detailed descriptions of the throughput analysis for a practical WSN with a limited number of users is given. The analytical model is verified using the Riverbed Modeler. The simulation results for throughput show a discrepancy between models for a finite node system and the current analytical model. As the spatial reuse of the network is limited by the antenna pattern, a discussion on the selection of the number of hub antennas is then given, based on achieving the highest possible throughput performance with realistic directional antennas. The analysis and simulation results show a 186% increase in throughput.**

Keywords— Medium Access Control, Wireless Sensor Network, Directional Antenna, Aloha.

I. INTRODUCTION

For contention based medium access control (MAC) protocols, with data transmission on a best effort basis, the throughput performance suffers due to packet collisions, especially under high offered loads. Directional antennas can be an effective approach in throughput improvement due to the enhanced spatial reuse. Many previous studies analysing the throughput of random access MAC protocols with directional antennas have assumed the use of idealised antenna patterns, where each antenna beam is distinct, with no overlap with adjacent beams; and often the antennas are assumed to have a constant gain across the beam [1-8]. Some analysis has assumed an infinite number of nodes in the wireless sensor networks (WSNs) [9-10].

In [9], we proposed a simple throughput analysis for the proposed directional hub MAC protocol for a star topology WSN based on the traditional Pure Aloha protocol. It is shown that although directional antennas can enhance throughput performance, the antenna pattern may have a significant effect on the spatial reuse and network performance due to the antenna pattern overlap. However, the throughput analysis assumed a close to infinite number of users in the WSN.

In this paper we present a new throughput analysis for Aloha based directional hub MAC protocols. Different from previous studies, it is shown that, when real antenna patterns are considered, increasing the number of hub antennas does not always improve the network performance. The effect of the number of hub antennas on the antenna pattern overlap is also discussed.

II. DIRECTIONAL HUB SLOTTED ALOHA (DH-SLOTTED ALOHA) PROTOCOL

A. Sensor Node Protocol

In this protocol, we consider a scenario where n sensor nodes gather data and contend for access to a single frequency channel by the means of a Slotted Aloha protocol [11]. Slotted Aloha is an extension from the Pure Aloha protocol. In the Slotted Aloha protocol, time is synchronised and divided into slots with a duration equivalent to the packet transmission time plus a short guard time. Sensor nodes transmit data packets at the beginning of the time slots. Packets arriving during ongoing transmissions will be added to the node's queue. On completion of each transmission, the node's queue is checked for further packets, and queued packets will be transmitted at the beginning of subsequent slots on a First-In-First-Out (FIFO) basis.

B. Hub Protocol

The proposed DH-Slotted Aloha protocol considers the use of a set of directional antennas at the hub, to provide spatial reuse of the channel with the aim of increasing the overall network throughput.

In order to demonstrate the effect of the antenna pattern on performance, simulations were performed with a real antenna pattern as shown in Figure 1 [9]. As we assume nodes may move, as may obstacles and sources of interference, the optimum hub antenna for each node must be allocated dynamically. Whenever the hub receives a packet from a node, it may be received by more than one antenna. The first data packet with a given packet ID received by any antenna will be passed to the data sink. The antenna choice for communicating with the sending node will also be updated to the corresponding antenna. If subsequent data packets are received with the same packet ID and have a higher receive signal quality, the antenna choice will be updated to reflect the best channel.

III. THROUGHPUT ANALYSIS FOR DIRECTIONAL HUB ALOHA PROTOCOLS

In this section analytical expressions are derived, and the throughput of a multi-directional antenna hub is compared with that of a single omni-directional antenna Aloha protocol.

There are two main types of Aloha protocol: The Pure Aloha and Slotted Aloha protocols. In the Pure Aloha protocol, devices can transmit packets using a shared channel as soon as the packets arrive in the queue, providing there is no on-going transmission. As there is no coordination required

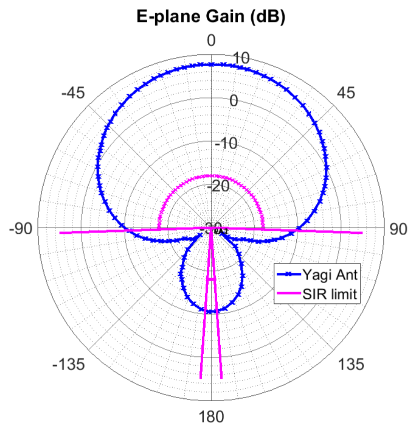

Fig. 1. Polar plot of antenna gain pattern of a realistic directional antenna with signal-to-interference ratio (SIR) limit angles.

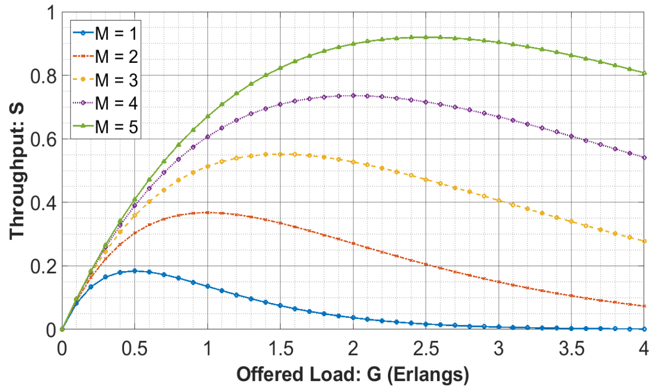

Fig. 2. Theoretical throughput of DH-Pure Aloha with M ideal antennas and an infinite number of nodes.

between devices to access the channel; if more than one device transmits at the same time, a collision will occur, and data may be lost. For a reliable network, a receiver will transmit acknowledgements back to the sender following the successful reception of data, enabling the sender to determine whether a collision has taken place and if retransmissions are required. Slotted Aloha is an extension from the Pure Aloha protocol, which can potentially provide twice the maximum channel throughput, with increased protocol complexity. In the Slotted Aloha protocol, time is synchronised and divided into slots with a duration equivalent to the packet transmission time and a short guard time. Devices transmit data packets at the beginning of time slots following their arrival. As a result, collisions only occur if more than one user transmits in the same slot. The decisive difference between the Pure Aloha and Slotted Aloha protocols is the period in which packet collisions are possible, two packet durations for Pure Aloha and one packet duration for Slotted Aloha. This difference halves the packet collision probability and results in a doubling of the throughput capability.

The analytical throughput model of Pure and Slotted Aloha, where a single antenna is used, is given by:

$$S_{Pure} = G\, e^{-2\,G} \tag{1}$$

$$S_{Slotted} = G\, e^{-\,G} \tag{2}$$

where S_{Pure} and $S_{Slotted}$ denote the network throughput in Erlangs and G is the overall offered load [11-12].

The probability of a packet arriving in each node from its upper layer is related to the overall network traffic offered load by:

$$p = \frac{1}{n} \tag{3}$$

where p is the probability of single transmission from a number of n nodes.

Therefore, the theoretical throughput S_{Pure} and $S_{Slotted}$ for Pure and Slotted Aloha with a finite number of sensor nodes are given in (4) and (5) respectively as in [13]:

$$S_{Pure} = \ n\, p\, (1-p)^{n-1}\, (1-p)^{n-1}$$

$$= \ n\, p\, (1-p)^{2(n-1)} \tag{4}$$

$$S_{Slotted} \ = n\, p\, (1-p)^{(n-1)} \tag{5}$$

In the single omni-directional antenna Aloha case, the theoretical throughput for Pure and Slotted Aloha are given by (1) and (2), respectively, with the assumption of a very large number of transmitting nodes. The number of directional antennas (M) is a key feature to the potential enhancement of spatial reuse in a WSN. When M ideal antennas without overlapping antenna beams are used at the hub, the system behaves as if there are M separate Aloha systems given that the sensor nodes are assumed to be equally distributed between the M antennas. The network traffic offered load to each antenna is $1/M$ of the total load, and the overall throughput (S_{Mno}) is M times as large as that of a single antenna system. The overall network throughput of such a system is therefore given by (6) [9] and (7). Figure 2 shows that the maximum achievable throughput is heavily dependent on the number of hub antennas.

$$S_{Mno\_Pure} = M\left(\frac{G}{M}e^{-2\frac{G}{M}}\right) \tag{6}$$

$$S_{Mno\_Slotted} = M\left(\frac{G}{M}e^{-\frac{G}{M}}\right) \tag{7}$$

In order to analyse the throughput performance of the DH-Aloha for practical systems, the analytical expressions for a finite number of sensor nodes can be derived from (4) to (7), with $M = 1$ as DH-Pure Aloha in (8) and DH-Slotted Aloha in (9):

$$\mathrm{S} = \mathrm{G}\left(\left(1-\frac{G}{n}\right)^{2(n-1)}\right) \tag{8}$$

where n is the number of sensor nodes within the network.

$$S = \mathrm{G}\left(\left(1-\frac{G}{n}\right)^{(n-1)}\right) \tag{9}$$

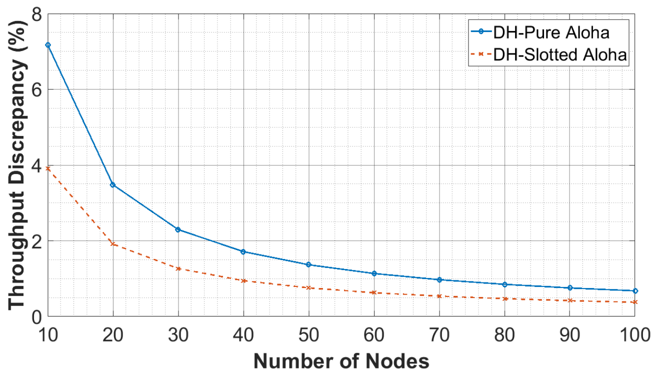

Fig. 3. The average throughput discrepancy of DH-Aloha throughput analysis with a finite node number over throughput analysis with infinite nodes.

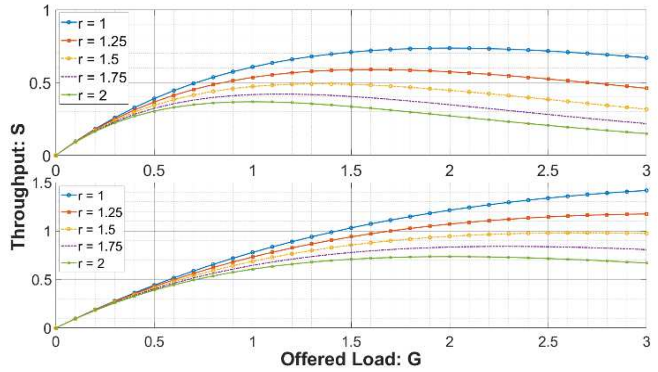

Fig. 4. The theoretical throughput of DH-Aloha protocols with $M = 4$ and a variation overlap factor r with DH-Pure Aloha on top and DH-Slotted Aloha at the bottom.

In (10) and (11), the theoretical throughput of the DH-Aloha protocol is given for a multi antenna hub, with M antennas having no overlap, and in which the network offered load to each antenna is $1/M$ of the total load with n nodes.

$$\begin{aligned} S_{Mno\_Pure} &= \mathrm{M}\left(\frac{G}{M}\left(1-\frac{G}{M\,n}\right)^{2(n-1)}\right) \\ &= \left(G\left(1-\frac{G}{M\,n}\right)^{2(n-1)}\right) \end{aligned} \quad (10)$$

$$\begin{aligned} S_{Mno\_Slotted} &= \mathrm{M}\left(\frac{G}{M}\left(1-\frac{G}{M\,n}\right)^{(n-1)}\right) \\ &= \left(G\left(1-\frac{G}{M\,n}\right)^{(n-1)}\right) \end{aligned} \quad (11)$$

Figure 3 shows the throughput difference of the DH-Aloha protocols with a finite and infinite number of nodes. The throughput discrepancy here can be defined as the difference between the maximum achievable throughput of the DH-Aloha protocols with a finite and infinite number of nodes. However, it is worth noting that as the number of sensor nodes approach a certain threshold, the network throughput discrepancy levels off to a near constant value. Although the analytical model for the infinite node case provides a close estimate for a WSN with a large number of nodes, the analytical model for a finite number of nodes can provide a more reliable upper bound throughput estimation for smaller WSNs.

IV. Antenna Pattern Overlap Effect with A Practical System

The throughput analysis in Section II provides the maximum potential throughput performance of the DH-Aloha protocols, where each directional antenna is idealised with constant gain across the antenna beam and no side or back lobes. However, overlap between the antenna patterns occurs in any practical system and the packets from sensor nodes in the overlapping regions may be received by multiple antennas, thereby resulting in a higher probability of collision [9]. Ideally each of the M antenna sectors should subtend an angle of exactly:

$$\theta_S = \frac{360}{M} \quad (12)$$

However, overlaps between adjacent antenna patterns will occur in any practical system to ensure full coverage of the network, and packets from sensor nodes in the overlapping regions may be received by multiple antennas, thereby resulting in an increasing probability of collision. If the angle of each antenna that can successfully receive packets is θ_A degrees, which is larger than θ_S to make sure the full coverage (azimuth plane) of sensor nodes, each antenna will see its offered load increased by a factor of r times the case with no overlap where:

$$r = \frac{\theta_A}{\theta_S} \quad (13)$$

Also, a proportion of the packets will be received by more than one antenna which further reduces the effective throughput by a factor of r. Therefore, the overall throughput with an infinite number of nodes is given by [9]:

$$S_{M\_Pure} = \frac{M}{r}\left(\frac{G}{M} r e^{-2\frac{G}{M}r}\right) = Ge^{\frac{-2\,G\,r}{M}} \quad (14)$$

$$S_{M\_Slotted} = \frac{M}{r}\left(\frac{G}{M} r e^{-\frac{G}{M}r}\right) = Ge^{\frac{-G\,r}{M}} \quad (15)$$

Figure 4 shows the theoretical throughput of the network throughput as a function of the offered load with a variation of r for the DH-Aloha protocols.

In order to determine θ_A, we must consider the signal-to-interference ratio (SIR). The SIR limit for directional antennas can be determined using the analysis in [9]. For the example in this paper, the required SIR for DH-Pure Aloha is 10.6 dB, and 19.17 dB for DH-Slotted Aloha, with $M = 4$, and the antennas used, which gives $\theta_S/2 = 45^o$, $\theta_{A0}/2 = 70^o$ for DH-Pure Aloha and $\theta_{A0}/2 = 90^o$ for DH-Slotted Aloha, and $\theta_A/2 = 81^o$ for DH-Pure Aloha and $\theta_A/2 = 99^o$ for DH-Slotted Aloha, as shown in Figure 5.

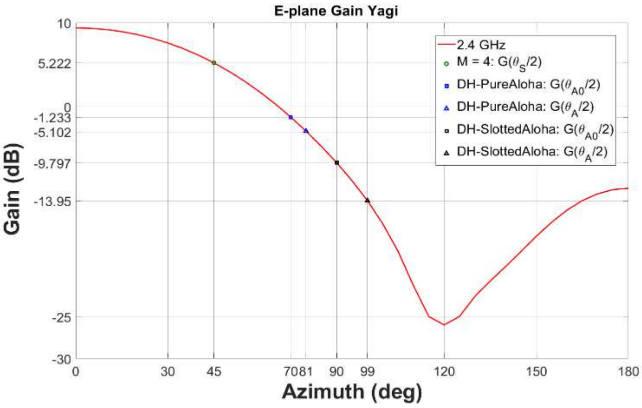

Fig. 5. The antenna gain relative to boresight for $M = 4$, at sector edge ($\theta_S/2$), the SIR limit for boresight node ($\theta_{A0}/2$), and the SIR limit for node at sector edge ($\theta_A/2$).

The difference in SIR limit for the same antenna pattern is due to the sensor node's behavior. When sensor nodes are transmitting by the means of Pure Aloha, packet overlap at the receiver can occur between 1 bit and the whole packet length. However, when sensor nodes are transmitting by the means of Slotted Aloha, interfering packets will always fully overlap with the original packet. This causes the increase in the required SIR.

Therefore, the theoretical throughput of the DH-Aloha protocols with M antennas can be defined as:

$$S_{DH-Pure} = \frac{M}{r}\left(\frac{G\,r}{M}\left(1-\frac{G\,r}{M\,n}\right)^{2(n-1)}\right) = G\left(1-\frac{G\,r}{M\,n}\right)^{2(n-1)} \tag{16}$$

$$S_{DH-Slotted} = \frac{M}{r}\left(\frac{G\,r}{M}\left(1-\frac{G\,r}{M\,n}\right)^{(n-1)}\right) = G\left(1-\frac{G\,r}{M\,n}\right)^{(n-1)} \tag{17}$$

where the network offered load to each antenna is $\frac{1}{M}$ of the total load with n nodes.

Figure 6 presents the throughput difference between the throughput with finite nodes and that with infinite nodes as a function of traffic offered load and overlap factor for different number of nodes. It shows that the throughput discrepancy between the two models is low when the number of nodes is high, but as the number of nodes decreases, the throughput discrepancy increases rapidly. The throughput performance prediction becomes less accurate as the number of nodes reduces, since the packet queue builds up due to on-going transmissions and fewer nodes are transmitting in the network. By considering the wide range of potential WSN applications, it is important to have both analytical models to provide reliable throughput performance prediction for different network topology scenarios.

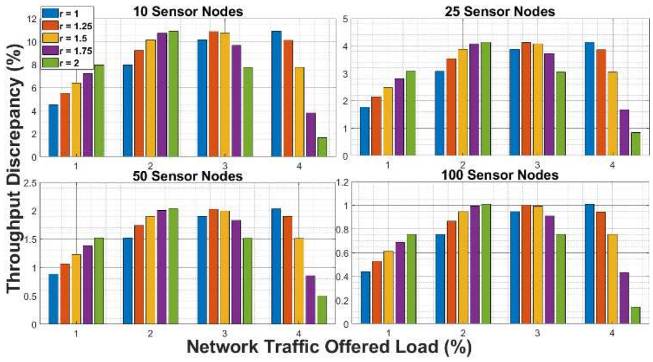

Fig. 6. Throughput discrepancy of finite node scenarios between analytical models for infinite and finite nodes.

Figure 7 shows the maximum achievable throughput of DH-Pure Aloha with different numbers of hub antennas as a function of antenna overlap factor at a 50% traffic offered load level. It is clear from Figure 7 that the maximum channel utilisation increases with the number of directional antennas at the hub. The number of antennas, however, is not completely related to higher channel utilisation. As it can be seen, with the same number of hub antennas, the upper bound throughput decreases as the overlap factor of the antenna increases. Although multiple directional antennas enhance spatial reuse, it might be more suitable to use less antennas for cost effectiveness in some scenarios. In the example shown, the upper bound throughput of $M = 4$ and $M = 5$ when $r = 1.49$ and $r = 1.71$ respectively, can actually be achieved with 3 hub antennas with $r = 1.2$. This is due to the fact that the hub node suffers from interference caused by the antenna overlap. Therefore, the analytical models for the DH-Aloha protocols are crucial to predict its throughput performance, especially when the number of sensor nodes and hub antennas could vary. Using (12) and (13), the achievable throughput of DH-Aloha with an antenna angle $\theta_A = 120^o$ was investigated. Figure 8 shows this throughput as a function of network offered load and M. Table 1 shows the value of overlap factor r as a function of antenna angle θ_A and M.

TABLE I. VALUES OF OVERLAP FACTOR r AS A FUNCTION OF ANTENNA ANGLE θ_A AND NUMBER OF HUB ANTENNA M.

Number of Antenna M \ Directional Antenna Angle θ_A	90	100	110	120	130	140	150	160	170	180
2	0.500	0.556	0.611	0.667	0.722	0.778	0.833	0.889	0.944	1.000
3	0.750	0.833	0.917	1.000	1.083	1.167	1.250	1.333	1.417	1.500
4	1.000	1.111	1.222	1.333	1.444	1.556	1.667	1.778	1.889	2.000
5	1.250	1.389	1.528	1.667	1.806	1.944	2.083	2.222	2.361	2.500
6	1.500	1.667	1.833	2.000	2.167	2.333	2.500	2.667	2.833	3.000
7	1.750	1.944	2.139	2.333	2.528	2.722	2.917	3.111	3.306	3.500
8	2.000	2.222	2.444	2.667	2.889	3.111	3.333	3.556	3.778	4.000

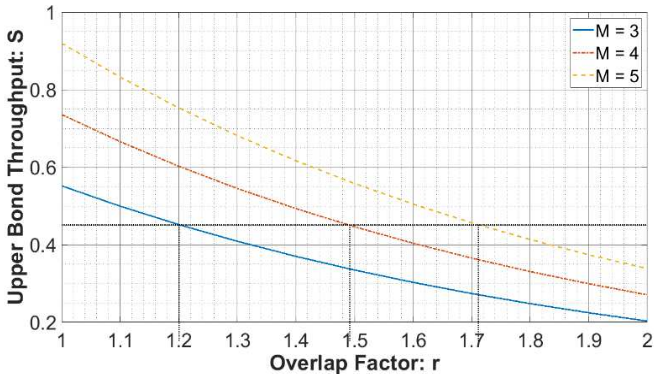

Fig. 7. The maximum throughput comparison of different antenna number M as a function of overlap factor $\boldsymbol{r}$ with 50 sensor nodes.

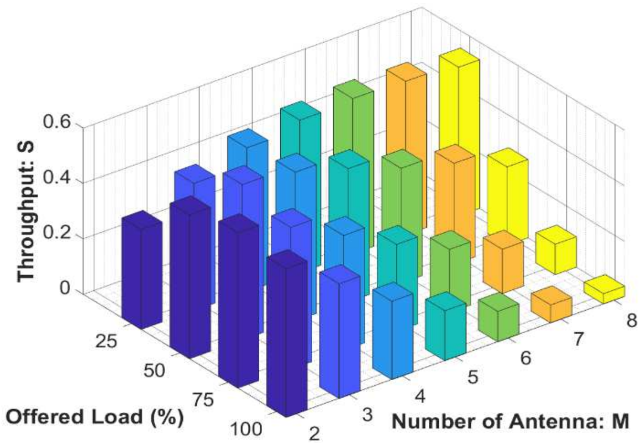

Fig. 8. The maximum achievable throughput comparison of different antenna number as a function of network offered load with 50 sensor nodes and $\theta_A = 120^o$.

As seen in Figure 8, using the same directional antenna pattern with $\theta_A = 120^o$, the throughput performance decreases as the number of hub antennas M and the network offered load increases. The value of r for this specific antenna pattern, with $M = 2$, is 0.667 (from Table 1), meaning there are gaps between the hub antennas. This results in lower achievable throughput, as packets from some sensor nodes might never be received. When $M = 3$, the value of r is equal to 1. In this scenario, maximum throughput can be achieved due to the maximum enhanced spatial reuse. When the hub has 4 or 5 antennas, the overlapping antennas indicate that, although the spatial reuse enhances throughput, it is limited by the overlapping region.

It is useful to compare the throughput performance against the overlap factor (r). Figure 9 shows the maximum achievable throughput of the DH-Pure Aloha protocol with 50% offered load as a function of overlap factor r and the number of hub antennas (M). It can be seen that in some cases a higher throughput can be achieved with fewer hub antennas with a smaller overlap factor r.

Therefore, analysis of the throughput performance using θ_A of the directional antenna pattern is essential in selecting the appropriate number of hub antennas for the directional hub WSN to achieve the highest possible throughput performance.

TABLE II. RIVERBED MODELER SIMULATION PARAMETERS.

Parameters	**Values**
Physical Layer	IEEE 802.15.4
Channel Bit Rate	250 kbits/s
Frequency Band	2.4 GHz
Data Packet Length	1024 bits
Number of Hub Antenna	4
Transmit Power	0.01 W
Number of Nodes	50
Network Area	100 x 100 m^2

V. SIMULATION

In order to evaluate and validate the proposed protocol, we consider a series of randomly generated topologies. 50 sensor nodes are randomly distributed around a central hub node using a pseudorandom number generator in a $100\ x\ 100\ m^2$ area, with the x and y coordinates uniformly distributed and independent. A single hub node is positioned at the centre of the deployment with four directional antennas (pointing N, E, S and W), with beam patterns as shown in Figure 1. All sensor nodes are equipped with an isotropic antenna with a transmission power of 0.01W and gain of 0 dBi. We consider free space propagation while all data packets are of the same length. Packet reception is governed by the received signal-to-interference-noise ratio (SINR), assuming uncoded binary phase shift keying (BPSK) modulation. A look up table is used to determine the bit error rate (BER) corresponding to the received SINR level. This BER value is used to determine whether each individual bit is received in error, based on the generation of uniformly distributed random numbers between zero and one, and comparison with the BER threshold. Packets are received if there are no bit errors (i.e. BER = 0). The key simulation parameters mirror those of an IEEE 802.15.4 system as shown in Table 2.

Figure 10 shows a comparison of the theoretical throughput of the standard, single antenna Pure and Slotted Aloha model, assuming 50 sensor nodes and Poisson traffic. The result of the Riverbed Modeler [14] simulation of the 50 random node WSN; the theoretical throughput predicted using (16) and (17) with $\theta_A/2 = 81^o$ for DH-Pure Aloha and $\theta_A/2 = 99^o$ for DH-Slotted Aloha.

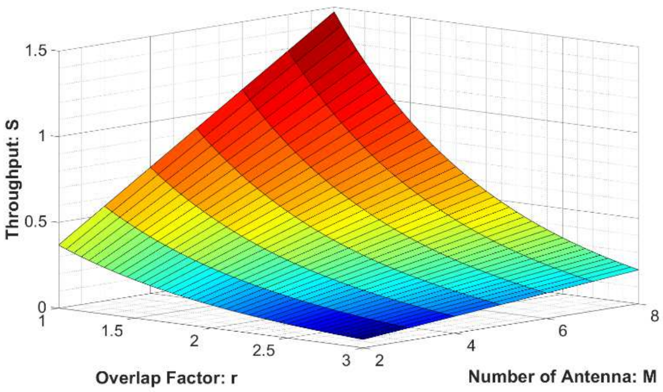

Fig. 9. The throughput performance of DH-Pure Aloha with 50% offered load as a function of overlap factor r and number of hub antennas M.

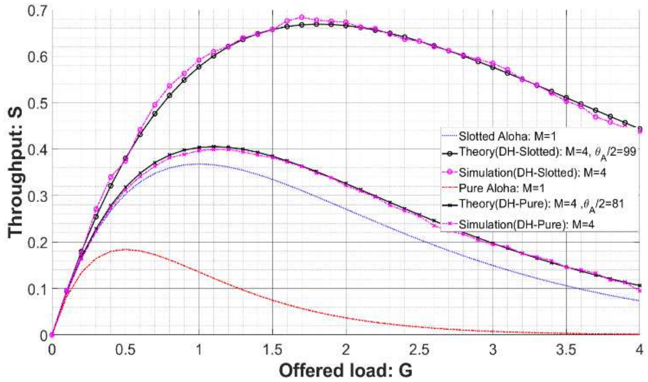

Fig. 10. The throughput of the DH-Aloha protocols with $M = 4$, comparing theory with simulation results.

VI. Conclusion

Two modified Aloha protocols, using directional antennas on a hub to receive data packets from a number of sensor nodes have been modelled using Riverbed Modeler and simulated with varying offered load. It is shown that the SIR limits for a given antenna pattern are different for different directional hub protocols. The performance of the DH-Pure Aloha protocol with 4 hub antennas proposed in [9] has a throughput of 2.17 times higher than the traditional Pure Aloha protocol with a single antenna-hub, whereas the proposed DH-Slotted Aloha protocol with 4 hub antennas has a throughput of 1.86 times higher than traditional Slotted Aloha with a single antenna hub This is due to the overlap factor r is much higher for the DH-Slotted Aloha protocol.

Further analysis has shown that using 3 directional antennas instead of 4, the DH-Slotted Aloha achieves a throughput of 1.82 times higher than the traditional Slotted Aloha with a single antenna hub. Although a greater number of directional antennas may provide enhanced throughput performance due to the enhanced spatial reuse, such gains are limited by the antenna pattern overlap region. Therefore, the analysis and results presented in this study are crucial in performance prediction and in deciding the number of hub antennas needed when applying directional hub protocols to WSNs.

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